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Simulated and Rocket-Triggered Lightning Testing of the Lightning- Invulnerable Device System (LIDS)

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ABSTRACT

We have developed a Lightning Invulnerable Device System (LIDS) to protect nuclear explosive test device systems at the U.S. Department of Energy's Nevada Test Site (NTS) against accidental detonation by lightning. In a series of full threat-level tests of a prototype LIDS canister, we used high-energy storage capacitor banks to generate high current rate of rise (di/dt = 200 kA/μs) and high-peak-current (200 kA), simulated-lightning, transient inputs to the LIDS. Subsequently, we participated in the NASA Rocket-Triggered Lightning Program (RTLP). In these experiments, a grounded wire is carried into a highly electrified cloud by a small rocket, causing the canister to be struck by actual lightning. Our results indicate that the LIDS provides an extremely effective way to prevent threat-level lightning transients from reaching the safety-critical components within the canister.

THE LIGHTNING PHENOMENON

Although the precise process involved in the electrification of storm cells continues to be a subject of research and discussion by atmospheric scientists, lightning's awesome and often deadly effects are well known. The lower portion of a mature storm cell is made up of negatively charged water droplets. This negative charge center is typically located 2.5 to 5 km above the ground. The corresponding positive charge center, made up of ice crystals, is found at elevations between 6 and 10 km. Estimates place the total charge in a storm cell at 1000 Coulombs within a volume of 50 km^3 (Ref. 1).

It should be noted that the following description of the lightning process is based on the "charged leader" concept introduced by Schonland[2] in 1938 and extensively cited and diversified over the years. An "uncharged leader" concept, not as widely accepted, was introduced in 1950 and further refined in recent years by Kasemir.[3]

Intra/Inter-Cloud Lightning

The strong electrostatic field within a cell leads to the development of ionized discharge channels, which neutralize charge centers of opposite polarity located either within the host cell (intra-cloud lightning) or in an adjacent cell (inter-cloud lightning). Intra/inter-cloud lightning accounts for the major portion of discharges in a thunderstorm. These discharges represent sources of strong electromagnetic fields, which can induce kilovolt-level transients in long horizontal power and communications lines and lead to circuit upset and component damage.[1,4]

Cloud-to-Ground Lightning

Under clear weather conditions the earth carries a negative charge with respect to the upper atmosphere. The magnitude of the resulting electric field gradient, which is perpendicular to the earth's surface and positive by convention, ranges between 100 and 300 V/m. As a thunderstorm cell approaches, the polarity of this field reverses under the influence of the cell's strong negative charge, and the magnitude of the gradient may exceed 20,000 V/m directly below the charge center.

The cloud-to-ground lightning process begins when the aforementioned ionized discharge channels emerge from the lower boundaries of the cloud and move toward the earth. Negative charge is deposited in each channel as it moves, in a series of discrete steps, toward pockets of positive charge in the intervening air. Known as the "stepped leader," this channel typically exhibits a number of branches extending out from the main channel.

As the faintly visible stepped leader nears the earth, it induces bound charge in ground objects. For pointed objects, ranging from poles and trees to raised golf clubs, rocks, and blades of grass, the electric field becomes very concentrated. When the stepped leader is between 30 to 100 m above ground, the critical charge density of the sharp objects is exceeded, ionization by collision occurs, and streams of positive ions are transported from the earth through the objects and into the air. These "ground streamers" exhibit currents from hundreds of microamperes to several milliamperes. When the rising streamers and descending step leader come to within10 m (the "striking distance"), a number of streamers join to close the remaining distance.[4]

With a cloud-to-ground electrical path established, negative charges stored along the leader channel flow to earth through the streamers. A unidirectional "high-current return stroke" proceeds up the channel to the cell's charge centers and continues until the original charge has been neutralized. Quite frequently, after a short interval (3 to 100 ms), a subsequent leader channel emerges from the cell. Because it follows the first stroke's ionized channel, it lacks branching and random steps and travels much faster, giving rise to the name "dart leader." Each dart leader produces a return stroke, and the entire event, comprised of all strokes, is referred to as a "lightning flash." A typical flash may exhibit four to six return strokes over 0.2 s to 1 s, although a maximum of 26 return strokes has been reported.[1] It is these multiple return strokes that cause a lightning flash to appear to flicker.

Cloud-to-Ground Lightning Parameters

While naturally occurring lightning exhibits a variety of waveshapes, the stroke current waveform is typically represented by a double-exponential having a high rate of rise, significantly lower rate of decay, and an extended "tail," or follow-on current[5] (see Fig. 1). In considering lightning as a threat to a nuclear device, we decided that only the effects of a severe (full threat-level) stroke should be taken into account. Industry and military standards generally consider a severe stroke to be one that lowers negative charge with a peak current of 200 kA and a maximum *di/dt* of 200 kA/μs (values that occur in less than 1% of all lightning strokes). A third important threat-definition parameter, the energy input or action integral ($I_{Pk}^2\, t_d$),* has a first-percentile value of 1.5×10^6 A^2-s (Ref. 6).

Positive Lightning

While the lightning so far discussed involves the lowering of negative charge (negative lightning), it should be pointed out that positive lightning also occurs, although much less frequently. It emerges from the high altitude, positively charged portion of a storm cell as a single stroke, often exhibiting much higher current than the more commonplace negative stroke. The *di/dt* is much less and the duration much longer than negative lightning.[1] It is believed to be responsible for the "bolt from the blue," lightning that appears to come out of a storm-free sky.

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* The energy contained in a lightning stroke can be expressed as

$$W = \int_0^t P\, dt = \int_0^t I^2 R\, dt = R \int_0^t I^2 dt \ , \tag{1}$$

where W = energy (J), P = power (W), t = stroke duration (s), I = current (A), and R = resistance (Ω).

One can see that the energy dissipated is very dependent on the value of R. If lightning strikes a metal flagpole (low R), little damage is done. If it strikes a tree (high R), the damage can be spectacular. To quantify the energy input when the resistance is not known, Eq. (1) is divided by R, yielding

$$\frac{W}{R} = \int_0^t I^2\, dt = I_{Pk}^2\, t_d \ , \tag{2}$$

which is referred to as the energy input, or *action integral*, with the units of A^2-s. The lightning-stroke duration, t_d, is defined as the time interval during which the current amplitude is greater than 50% of its peak value, I_{Pk}.

LIGHTNING AT THE NTS

Although lightning occurs at the NTS throughout the year, the greatest activity is between May and September.[7] While the probability of a lightning-induced detonation of a test device is considered to be "vanishingly small," the consequences would be absolutely unacceptable. Therefore, periodic safety studies have been conducted to ensure that the best techniques are being employed for mitigating the effects of a lightning strike.[8–10] In 1983, LLNL, in close cooperation with Sandia National Laboratories, Albuquerque, NM (SNLA), conducted an investigation of lightning vulnerability that led to the development and subsequent testing of the LIDS.[4] An overview of this investigation can be found in Refs. 11 and 12.

LIDS

In principle, the LIDS surrounds the nuclear-explosive test device and its associated components with a "fortress," a topologically closed, metallic surface (i.e., a Faraday cage). In practice, the fortress must be penetrated in order to accommodate power, instrumentation, and control lines. The electrical conductors that penetrate the fortress are protected by shields that are terminated at the outer surface of the fortress by means of 360° backshell connectors, which mate with bulkhead-mounted feedthrough connectors (see Fig. 2).

If the cables are struck by lightning, the current will divide among the shields and be conducted to ground via the lowest impedance path. If the strike point is relatively close to the LIDS, and the LIDS is in proximity to ground, a major portion of the current will flow through the shields and 360° backshell connectors to the fortress skin, and arc to the nearest grounded object.

A small portion of the lightning current is carried by the penetrating conductors, which provide paths to ground via various device-system components within the interior of the canister. With the LIDS, all such conductors must pass through transient limiters located inside the fortress, immediately after the feedthrough connectors. The limiters shunt most of the residual lightning current directly to ground, reducing the amplitudes of the transient voltages and currents that reach the device-system components to acceptably low values. The electrical requirements for each particular component determine whether the transient limiter will be a gas-filled spark gap (or metal-oxide varistor for ac power circuits) or a hybrid consisting of a spark gap, series impedance, and silicon avalanche diode (see Figs. 3 and 4).

SIMULATED LIGHTNING TESTING

Although a lightning simulator capable of producing a severe pulse exists at SNLA, we decided to first employ a damped-sine wave test waveform. This ensured that we would be able to perform a large number of tests without experiencing the damage expected from the double-exponential pulse and follow-on current of the SNLA simulator. We delivered the prototype LIDS canister to the Florida facilities of the Lightning & Transients Research Institute (LTRI), where we conducted a series of low-level, high-*di/dt*, and high-current tests.

Low-level Tests

First, we conducted low-level tests to determine the electrical characteristics of the system. After positioning the canister horizontally on a metallic sheet ground plane, we charged a small capacitor (2500 pF) to approximately 12 kV and discharged it to a conductor that penetrated into the LIDS via a connector and bulkhead feedthrough. The conductor was contained within a cable of the same type as used for "downhole" applications at the NTS (MC-17 multiconductor, RF-14 coaxial). We used a 0.5-m-long cable to keep the inductance small. Input current and transient voltage waveforms were recorded with an HP54200A, 200-MHz, dual-channel, digital oscilloscope.

High *di/dt* Tests

Next, we ran tests to determine how effectively the transient limiters would protect various system components in the presence of a severe *di/dt*. To do this, we used a Marx generator consisting of forty 1.6-μF, high-energy, storage capacitors. After the capacitors were charged in parallel through resistors to 35 kV, triggered spark gaps switched them in series, producing 1.4 MV across a 0.4-μF capacitance. The resultant energy (approximately 40 kJ) discharged into a large wire grid, 6 m overhead and well insulated from ground, which functioned as a peaking capacitor of about 750 pF (see Fig. 5). A low-inductance down-lead carried the charge to a 48-cm-wide ball spark gap, which was connected to a cable conductor, as described earlier. The high-voltage, high-*di/dt* pulse was applied to the transient limiter being exercised, breaking it down and allowing the generator current to flow to the LIDS structure and then to ground (see Fig. 6). The resulting input-current waveform consisted of a 145-kHz underdamped sine wave with a peak of approximately 50 kA (see Fig. 7). The effect of the peaking capacitor and down-lead inductance was to produce a 4-MHz damped oscillation, which was superimposed onto the leading edge of the 145-kHz wave. The steep leading edge of the 4-MHz wave produced a *di/dt* in excess of 200 kA/μs (see Fig. 8). The limiter conducted the full transient current to ground and was thus subjected to an action integral of 2×10^4 A^2-s.

High-Current Tests

Finally, we discharged severe peak currents into the cable's overall shield to determine what portion of the applied current would actually penetrate into the LIDS and how the limiters would perform. Thirty-nine of the Marx generator capacitors were relocated close to the LIDS and wired in parallel, providing 62.4 μF. After charging the capacitors to 33 kV (energy = 34 kJ), we discharged them by means of a remotely operated paddle switch into the shield, producing a 20-kHz damped sine wave with a peak current of 200 kA and a *di/dt* of about 15 kA/μs. The corresponding action integral was 1.8×10^6 A^2-s, which is somewhat higher than the value associated with a severe lightning stroke.

Results

We subjected coaxial limiters—of both the spark-gap-only and hybrid types (for the RF cables) and multichannel, hybrid, limiter modules (for the MC cables)—to hundreds of high-*di/dt* and high-current discharges. We measured the total current applied to the system and transient voltages at the inputs and outputs of the limiters under open-circuit and typical load conditions. For the high-current tests, we also measured residual current penetrating into the canister. All limiters performed as expected, holding voltages to safe levels. We found residual current to be between 5 and 10% of the applied current, well within the capabilities of the limiter components.

ROCKET-TRIGGERED LIGHTNING

Background

The behavior of natural lightning is best described as capricious, and attempts to predict where it may strike must be statistically determined. For this reason, lightning simulators are used to evaluate the lightning vulnerability of test articles. However, the real measure of how well a structure or system is protected from the effects of a nearby or direct strike is its response to actual lightning. Even in an area of high lightning incidence, one might wait years to get struck and then wait even longer to experience a second strike.

Direct electrical connection to a charged storm cell was first suggested by Benjamin Franklin, with his famous experiment with kite, string, and key. Fortunately for Ben, he did not experience an actual lightning stroke. Apparently, the second such experimenter, a less than fortunate Russian, died as a result of that dangerous technique. Since then, various, sometimes fatal, schemes have been tried to harness lightning.

In 1965, M. M. Newman, then Research Director of LTRI, introduced a variation of Ben Franklin's method into the 20th century.[13] By substituting a rocket for the kite and a grounded metallic wire for the string, the feasibility of triggering a cloud-to-ground lightning flash was demonstrated. The LTRI launching and instrumentation equipment was located aboard a small ship. This permitted the researchers to sail to where the lightning storms were most likely to be found. Over the years, LTRI has used this method to test a variety of military and civilian aircraft, spacecraft, and missile components.[14]

Ground-based, rocket-triggered, lightning research has been conducted in France since 1973 by scientists from the government organization Centre d'Etudes Nucleaires de Grenoble (CENG). Since 1979, the French have also joined American scientists to conduct experiments in the United States. During the summers of 1979, 1981, and 1982, these tests were carried out at the Langmuir Laboratory for Atmospheric Research, Soccorro, NM, operated by the New Mexico Institute of Mining and Technology. The facility is located at an elevation of 3240 m above sea level, near South Baldy Peak in the Magdalena Mountains of the Cibola National Forest. During the 1982 period, SNLA first became involved in triggered lightning.[15]

In 1983 the French moved their operation to sea level at Valkaria AFS near Melbourne, FL where they participated in NASA's Rocket Triggered Lightning Program (RTLP). During the summers of 1984 through 1986, the RTLP has been conducted at the J.F. Kennedy Space Center (KSC), which is in a region that has one of the highest frequencies of thunderstorm and lightning activity in the United States.

The KSC also has one of the world's most advanced weather-forecasting facilities, the Meteorological Interactive Data Display System (MIDDS), which has access to world-wide meteorological data and weather satellites, local radar, a sounding system, and an expanded mesonetwork of 50 stations.

RTLP

The RTLP is a broadly based, NASA-sponsored, interagency program. In addition to NASA, participants include the U.S. Air Force and Navy, the Federal Aviation Administration, scientists from several French organizations, and private-sector researchers from Bell Laboratories, the State University of New York at Albany, the University of Florida, and the University of Arizona. As a result of an invitation from NASA, LLNL was given the opportunity to test the LIDS canister with natural lightning during RTLP-86. SNLA, in continuing to provide excellent and essential support, found itself once again involved in rocket-triggered lightning. Participation in this well-established program offered opportunities for consultation with outside experts, as well as the benefits of technology transfer.

Located on (aptly named) Mosquito Lagoon, 15 km north of NASA's Vehicle Assembly Building, the RTLP test area (shown in Fig. 9) includes the Atmospheric Sciences Field Laboratory (ASFL), a rocket-launch platform, and a control and data-acquisition facility (a surplus, all-metal, railroad caboose).

Launch System and Lightning-Strike Object

A stand containing 12 rocket-launch tubes sits on a wooden platform approximately 4 m above ground level. Plastic-bodied, 1-m long, black-powder fueled rockets (provided by CENG and used by French farmers for cloud seeding) are loaded into the launch tubes. Affixed to the tail of each rocket is a spool containing a1-km length of small-diameter wire, jacketed with Kevlar to provide strength. The bottom ends of the wires are connected to the rocket launch stand, which is tied to the system ground plane, a horizontal grid of copper wire at the same elevation as the platform. The grid is connected, via a number of down conductors, to a counterpoise grounding system. Rocket launching is controlled by pneumatic signals emanating from the control and data-acquisition facility.

In previous years, the Air Force provided the RTLP lightning-strike object (LSO), a 12-m-long, instrumented, metal cylinder that simulates an aircraft fuselage. For 1986, the LSO was LLNL's 2.7-m long, 2.3-kg LIDS canister, which was placed on the platform adjacent to the launch tubes. Suspended 7 m above the canister, by a pair of wooden utility poles and a crossbar, was a horizontal metal pipe, which functioned as a lightning rod (see Fig. 10). A metal pulley was suspended from the center of the crossbar and electrically connected to the rod by a short piece of wire rope. An insulated line was used to haul a test cable (MC-17 or RF-14) up to the pulley. Removal of the cable's insulating jacket allowed its outer shield to be brought into direct electrical contact with the pulley. The upper end of the cable, approximately 1 m beyond the pulley, was terminated by shorting its shield(s) to its conductor(s). The lower end of the cable was mated to a LIDS bulkhead feedthrough by means of a 360° backshell connector. The base of the canister was connected to the grounding system via the rocket launch stand. Current was expected to flow from a lightning channel to the rod, through the pulley into the cable shield, down the shield into the LIDS metallic skin, and finally to ground.

Instrumentation

We measured the current applied to the LIDS (using a 250-kA Pearson coil, which we also used in the simulated lightning tests) and the corresponding voltages and currents that appeared within the canister. The lower end of the test cable passed through the coil just prior to entering the canister. A 10-kA Pearson coil, located beneath the LIDS top plate, measured the total internal current being conducted to ground by the transient limiter(s). Other sensors within the canister monitored transient voltages and currents to which the device-system components were subjected. An EG&G B-dot probe, positioned within the upper compartment of the canister, provided data on the rate of change of the magnetic flux. All electrical signals were converted to optical signals by the use of battery-powered, Nanofast OP-300, fiber-optic transmitters.

Data-Acquisition System

The all-metal caboose was well grounded, and all signal and control connections to and from the launch platform utilized either pneumatic or fiber-optic links. During test periods, ac power was provided by a diesel generator located right next to the caboose. Power-wire penetrations were made via appropriate transient limiters. As a result, we never experienced system upset or damage from the triggered lightning strikes, which were only 50 m away.

Our data-acquisition system (see Fig. 11) consisted of seven HP-54200A, 200-MHz, dual-channel, digital oscilloscopes, triggered simultaneously when the lightning input current reached a level of 4 kA. Immediately following the acquisition, an HP-300 computer system automatically stored all of the 'scope setup information and data on a floppy disk. One drawback was that this system could record only data associated with the first stroke that had an amplitude in excess of the trigger level. For this reason, a LeCroy digitizing oscilloscope was also used, allowing us to record the input current waveforms of flashes that had as many as eight return strokes.

Launch Scenario

As a storm cell approached the RTLP site, we monitored the electric-field gradient using a system of instruments known as electric-field mills (EFM). The field would gradually change from the +300 V/m "clear day" gradient to a large negative value. At first, natural lightning discharges would occur, temporarily reducing the field strength. We would not launch at this time because the occurrence of natural lightning concurrent with the launch would eliminate the possibility of triggering lightning. Conditions were considered satisfactory when the frequency of natural lightning flashes fell off and the local electric field (measured with CENG's downward-looking EFM located in a clear area approximately 25 m from the caboose) remained above −4 kV/m.

The French scientist would then initiate a short (5 to 10 s) countdown, followed by the launching of a single rocket. Once the 1-km-long wire was sufficiently close to the storm cell overhead, a discharge current of several hundred amperes would flow, vaporizing the wire in a bright flash and leaving an airborne ionized channel in proximity to the horizontal rod. We believe that, since the ionized channel exhibited a significant inductive reactance, the increasing rate-of-rise of channel current soon led to a very high channel-to-ground voltage ($V = L \cdot di/dt$). The path from rod to ground, via the LSO, represented a lower impedance than that provided by the bottom part of the vaporized wire. Thus, when the channel voltage exceeded the breakdown value for air, a channel-to-rod arc occurred, and a high-current return stroke flowed.[16] Typically, there was a delay of several hundred milliseconds between the wire burn and the first return stroke.

SUMMARY OF RTLP-86 RESULTS

During the test period, August 1 through September 15, 1986, storm activity was much lower than normal for that time of year. Five storms passed close enough to permit the triggering of 22 flashes, producing between 80 and 100 return strokes that were conducted to ground via our test system. A maximum peak current of 52 kA was recorded on the LeCroy 'scope, but the largest stroke for which a full complement of system response data was recorded was 40 kA (both from the same flash). Table 1 contains a complete summary of RTLP-86 strokes. Presently, no attempt has been made to explain the several apparent differences.

Figure 12 shows a vaporized wire trail and the resulting triggered lightning return stroke attached to the horizontal rod. Figure 13 shows a close-up of a wire burn, as well as multiple return strokes.

We individually subjected one multiconductor and two coaxial cables to lightning return strokes. As in simulated lightning tests, the LIDS design concept was shown to provide significant protection from the effects of a direct strike to the cable. In the case of the MC-17, we measured 3 kA of total internal current in conjunction with a 29-kA stroke. Since the internal current was carried to ground by 36 parallel, 20-kA limiters, the average per-channel, transient current was less than 100 A.

Because the RF-14 cable's solid shield provides nearly perfect shielding, the 40-kA stroke produced no detectable internal current. In all cases, the transient voltages and currents reaching the device system's safety-critical components were limited to absolutely safe amplitudes.

CONCLUSIONS

The single objective of the LIDS is to provide a device canister that can sustain any magnitude of (including severe) lightning strike directly to its cables without exposing the safety-critical components to threat-level energy. We have tested a prototype LIDS against severe levels of simulated lightning, as well as typical levels of natural lightning. While the RTLP tests utilized a single cable, NTS downhole device systems typically employ eight or more cables. A lightning strike to an actual system would result in all of the cables dividing the current essentially equally (i.e., a 200-kA stroke would cause each cable to carry 25 kA or less. Thus, the single-cable current of many of our rocket-triggered lightning strokes approached or exceeded an equivalent of 200 kA.

The major portion of all simulated and natural lightning currents were carried to ground via the cable shield, 360° backshell connector, and canister skin. Residual currents penetrating into the interior of the canister were significantly lower than the ratings of the limiters through which they were conducted to ground. Voltage and current transients were held to levels known to be safe. Implementation of techniques known to be effective in mitigating lightning-hazard effects were successfully demonstrated. All indications are that this design concept will provide a device system that is invulnerable to lightning.

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Without the assistance and enthusiasm of W. Jafferis, NASA/KSC, we would have neither known about nor been able to participate in RTLP-86. The entire LIDS/RTLP-86 effort, from the initial site visit through post-experiment site dismantling, was a scant four months. Without the skills and "lightning" responses provided by the aforementioned persons, plus J. Lamb, LLNL, and R. Jones, EG&G/Florida, this project could not have come to fruition in such a short time.

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Table 1. RTLP-86 lightning-flash summary.

Storm No.	Date (EDT)	Time (GMT)	Electric field gradient (kV/m) at launch	Flash I.D. No.			Peak stroke current (kA)								Notes
				CENG[a]	LLNL[b]	PRC[c]	1	2	3	4	5	6	7	8	
1	8/13	19:30	−3.8	8607			10	–	–	–	–	–	–	–	
					01		11	–	–	–	–	–	–	–	d
						–	–	–	–	–	–	–	–	–	
		19:37	−4.1	8608			5	–	–	–	–	–	–	–	
					02		4	–	–	–	–	–	–	–	d
						–	–	–	–	–	–	–	–	–	
		20:35	−3.7	8610			8	26	12	<6	11	–	–	–	
					03		7	22	14	7	15	–	–	–	d
						–	–	–	–	–	–	–	–	–	
		20:57	−5.1	8615			14	15	6	14	7	8	6	8	
					04		14	13	8	13	8	10	–	–	d
						–	–	–	–	–	–	–	–	–	
		21:04	−5.2	8616			–	–	–	–	–	–	–	–	
					05		22	8	10	–	–	–	–	–	d
						–	–	–	–	–	–	–	–	–	
		21:06	−5.6	8617			7	15	7	–	–	–	–	–	
					06		<4	13	<4	–	–	–	–	–	d
						–	–	–	–	–	–	–	–	–	
2	8/14	21:19	−5.2	8618			23	31	22	–	–	–	–	–	
					07		22	–	–	–	–	–	–	–	d, e
						1	20	25	–	–	–	–	–	–	105[f]
		21:24	−5.8	8619			17	14	19	20	–	–	–	–	
					08		21	21	–	–	–	–	–	–	d
						2	18	17	–	–	–	–	–	–	66[f]
		21:32	−5.3	8620			33	8	28	<6	19	–	–	–	
					09		29	8	23	5	16	–	–	–	d
						3	26	8	20	4	14	–	–	–	109[f]
		21:35	−5.9	8621			8	30	<6	29	8	8	–	–	
					10		8	27	8	24	8	10	–	–	d
						4	6	25	6	23	6	10	–	–	116[f]
		21:38	−5.5	8622			28	26	–	–	–	–	–	–	
					11		29	25	–	–	–	–	–	–	d
						5	25	22	<3	–	–	–	–	–	104[f]
		21:48	−5.8	8623			7	8	13	<6	22	–	–	–	
					12		8	–	–	–	–	–	–	–	d, g
						6	6	7	12	6	19	–	–	–	88[f]

[a] Data from CENG current shunt, including LIDS current plus any other current bypassing the LIDS and reaching ground via the rocket launch stand.
[b] Data from LLNL current monitor.
[c] Data from LLNL current monitor, recorded and processed by PRC.
[d] MC-17 cable.
[e] No LeCroy data after 1st stroke.
[f] Max di/dt (kA/μs).
[g] No LeCroy data.

Table 1. (Continued).

Storm No.	Date (EDT)	Time (GMT)	Electric field gradient (kV/m) at launch	Flash I.D. No. CENG[a]	LLNL[b]	PRC[c]	Peak stroke current (kA) 1	2	3	4	5	6	7	8	Notes
3	8/20	17:26	−5.0	8626			41	<6	36	55	25	<6	38	–	
					13		40	8	34	52	22	7	–	–	h
						–	–	–	–	–	–	–	–	–	
		17:28	−5.1	8627			19	12	10	–	–	–	–	–	
					14		19	11	13	–	–	–	–	–	h
						–	–	–	–	–	–	–	–	–	
4	8/28	21:31	−6.3	8628			–	–	–	–	–	–	–	–	
					15		9	8	14	25	14	17	11	19	h, i
						15	9	8	13	23	14	16	10	18	75[f]
		21:40	−6.3	8629			12	16	<6	–	–	–	–	–	
					16		6	18	6	–	–	–	–	–	h, i
						16	5	17	6	–	–	–	–	–	
		21:44	−6.1	8630			16	16	–	–	–	–	–	–	
					17		17	18	–	–	–	–	–	–	h, i
						17	16	17	–	–	–	–	–	–	54[f]
5	8/29	22:54	−4.7	8634			15	6	8	7	6	<6	32	–	
					18		16	5	10	13	9	6	16	–	h, i
						18	15	4	9	11	8	5	15	–	83[f]
		23:05	−4.7	8635			<6	<6	13	11	19	17	16	–	
					19		6	6	10	8	11	–	–	–	h, i
						19	4	6	10	8	5	–	–	–	82[f]
		23:07	−4.7	8636			39	12	10	–	–	–	–	–	
					20		14	8	6	–	–	–	–	–	h, i
						20	14	7	6	–	–	–	–	–	61[f]
		23:11	−4.9	8637			26	8	<6	–	–	–	–	–	
					21		5	12	5	–	–	–	–	–	h, i
						21	4	11	5	–	–	–	–	–	61[f]
		23:17	−5.0	8638			10	7	11	6	–	–	–	–	
					22		7	6	7	6	–	–	–	–	h, i
						22	8	5	6	5	–	–	–	–	59[f]

[a] Data from CENG current shunt, including LIDS current plus any other current bypassing the LIDS and reaching ground via the rocket launch stand.
[b] Data from LLNL current monitor.
[c] Data from LLNL current monitor, recorded and processed by PRC.
[d] MC-17 cable.
[e] No LeCroy data after 1st stroke.
[f] Max di/dt (kA/μs).
[g] No LeCroy data.
[h] RF-14 cable.
[i] TC-185, 500-V CTL (not discussed in text).

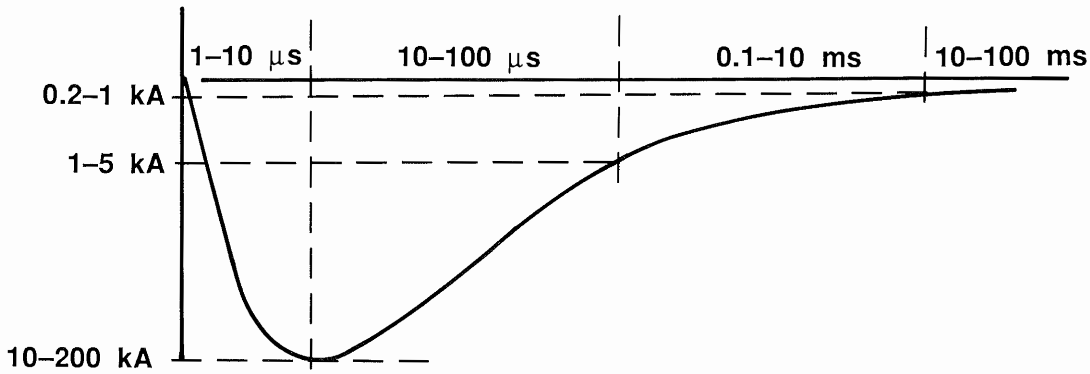

Figure 1. While naturally occurring lightning exhibits a wide variety of waveshapes, the waveform of the stroke current is typically a double exponential with a high rate of rise, significantly lower rate of decay, and an extended ''tail,'' or follow-on current.

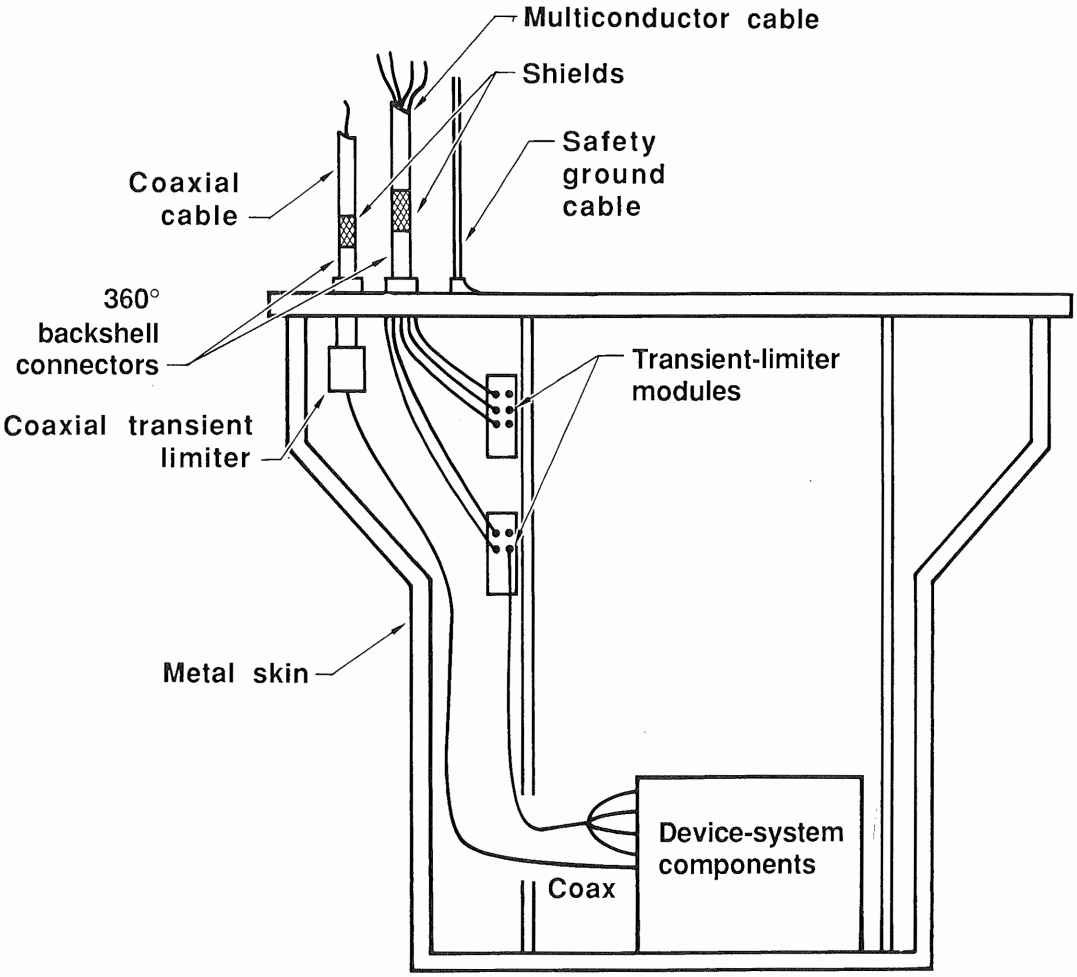

Figure 2. A simplified sketch of the lightning-invulnerable device system (LIDS). The electrical conductors that penetrate the fortress are protected by shields that are terminated at the outer surface of the fortress by means of 360° backshell connectors, which mate with bulkhead-mounted feedthrough connectors.

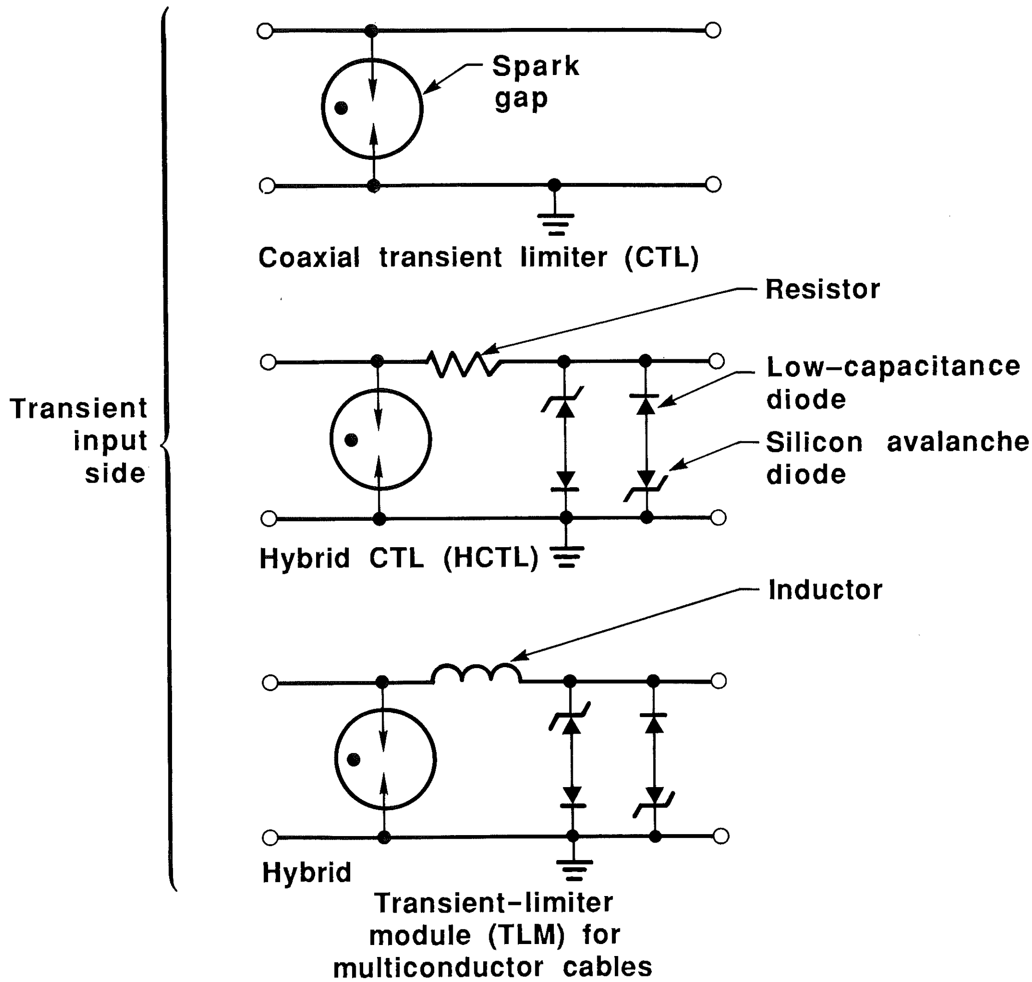

Figure 3. The electrical requirements for each device-system component determine the type of transient limiter to be used. A transient limiter may be a gas-filled spark gap (or a metal-oxide varistor) or a hybrid consisting of a spark gap, a series impedance, and a silicon avalanche diode.

Figure 4. Transient limiters mounted in the LIDS canister.

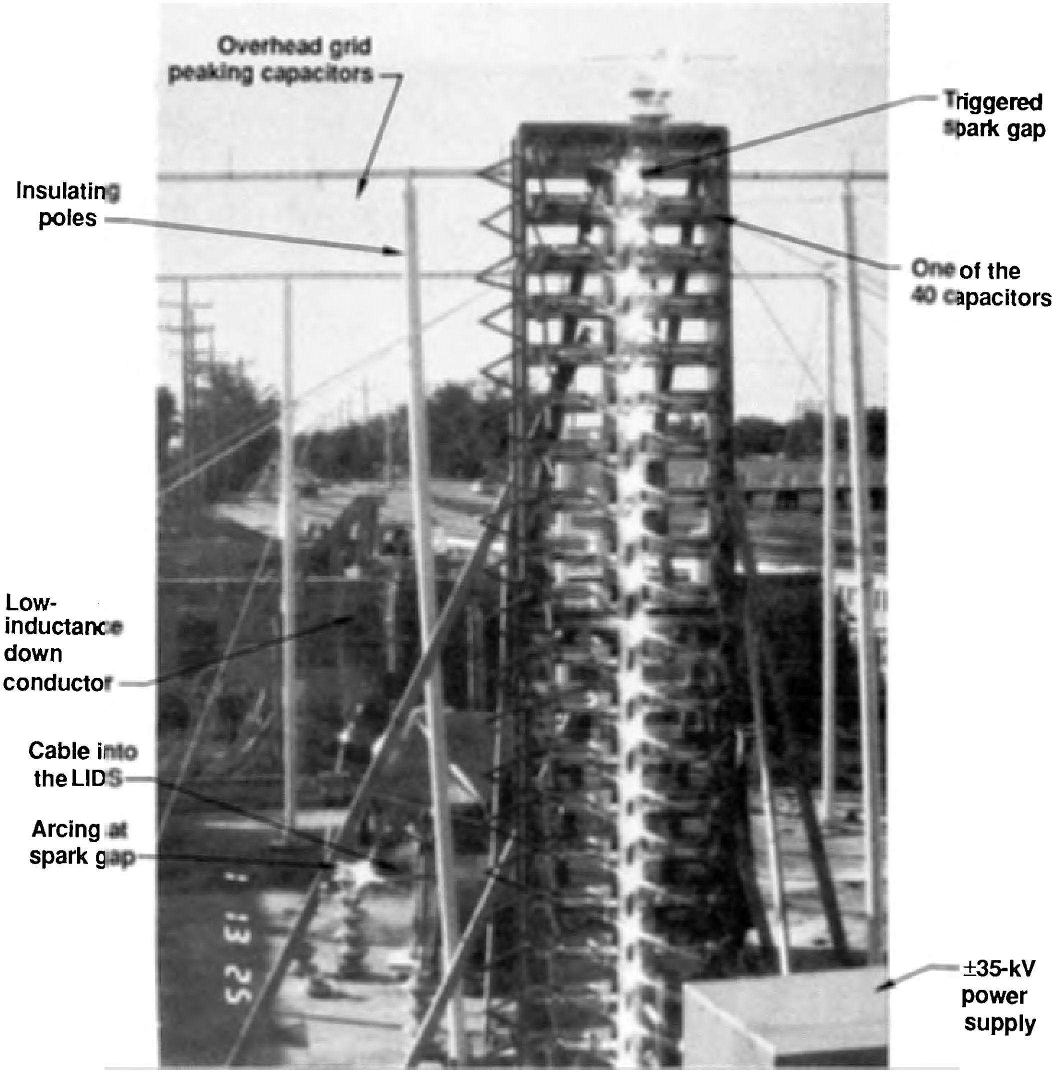

Figure 5. The Marx generator discharging 1.4 MV to produce a 200-kA/μs, simulated-lightning input to the LIDS canister.

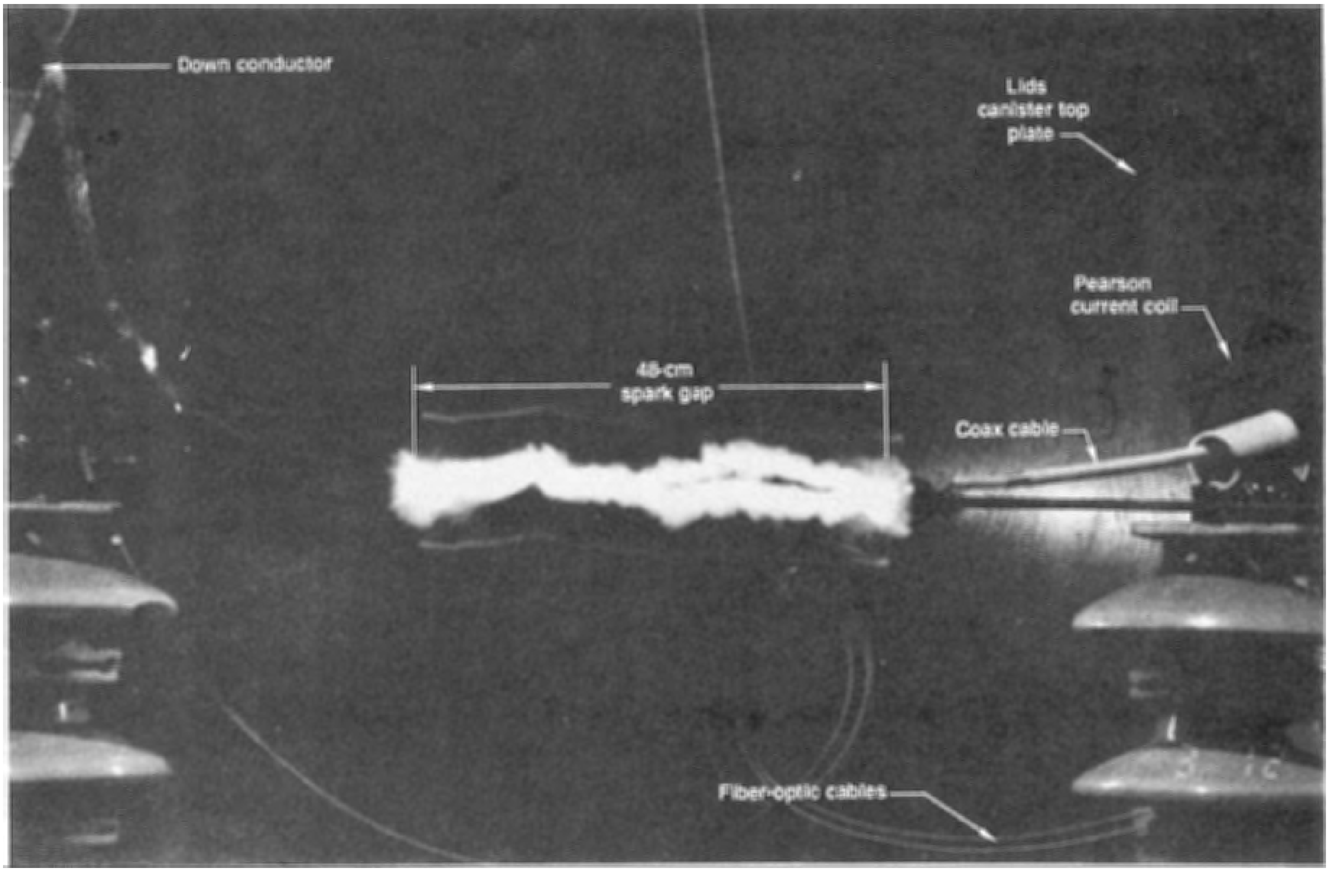

Figure 6. A 200-kA/μs, 48-kA, peak current discharging into the center conductor of a coax cable.

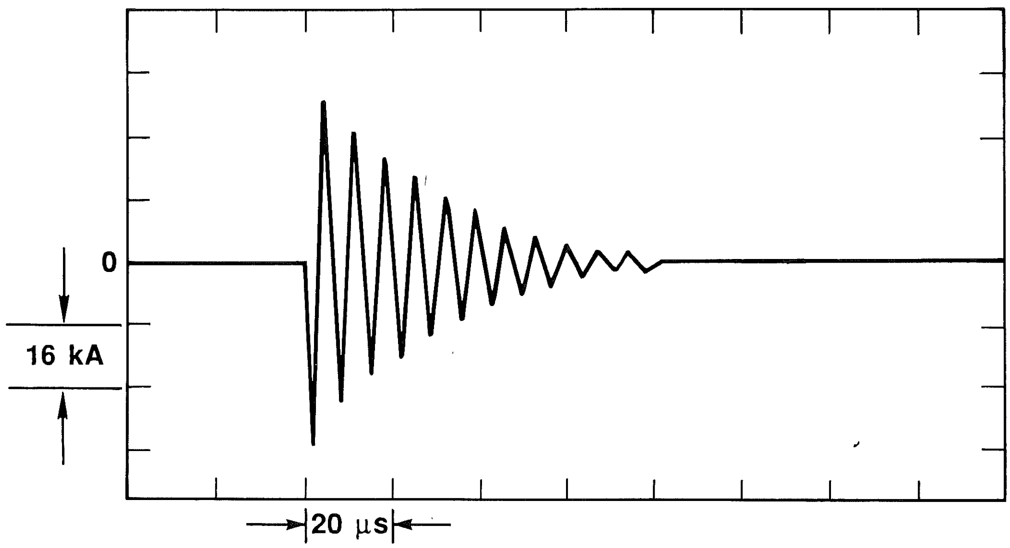

Figure 7. Oscillogram of a Marx generator-produced, 145-kHz, damped-sine-wave current to the LIDS canister.

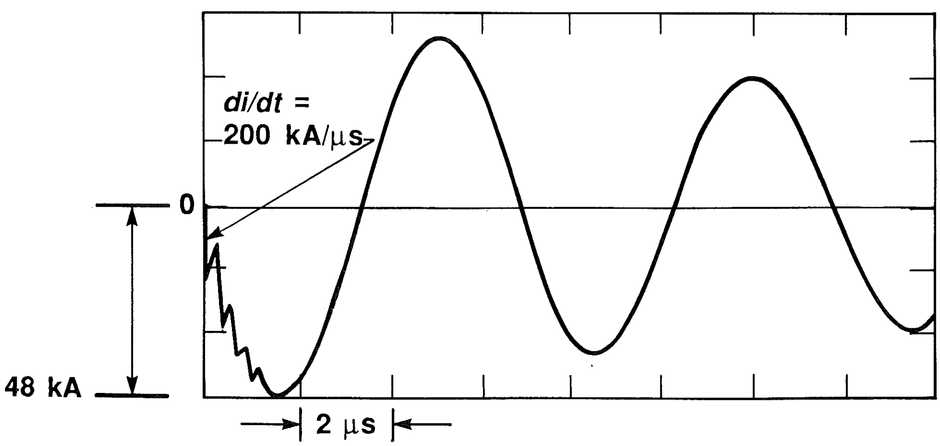

Figure 8. Expanded view of Fig. 7, showing 4-MHz ringing on the leading edge to obtain high *di/dt*. The steep leading edge of the wave produced a *di/dt* in excess of 200 kA/μs.

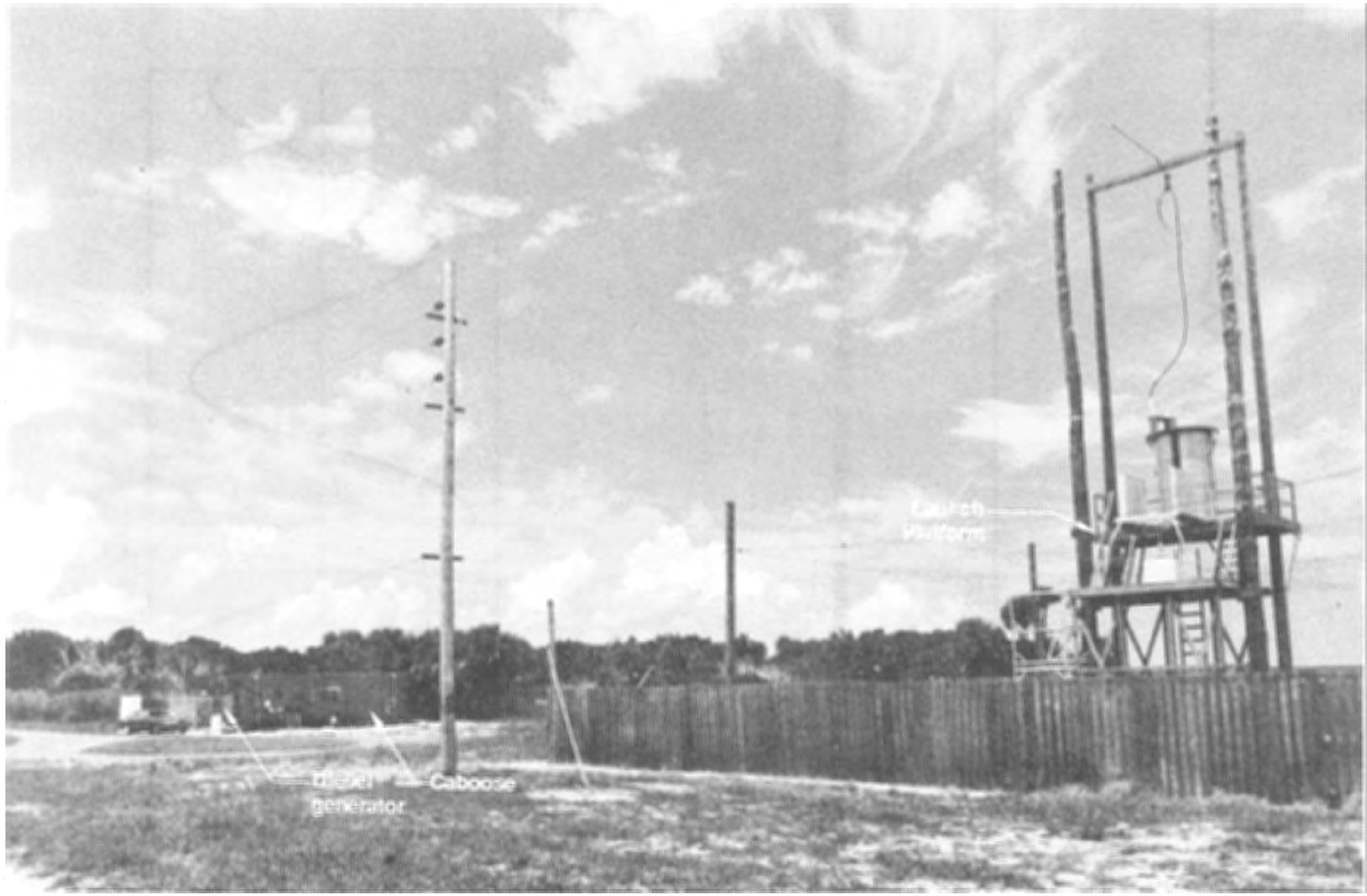

Figure 9. The RTLP test area at Mosquito Lagoon.

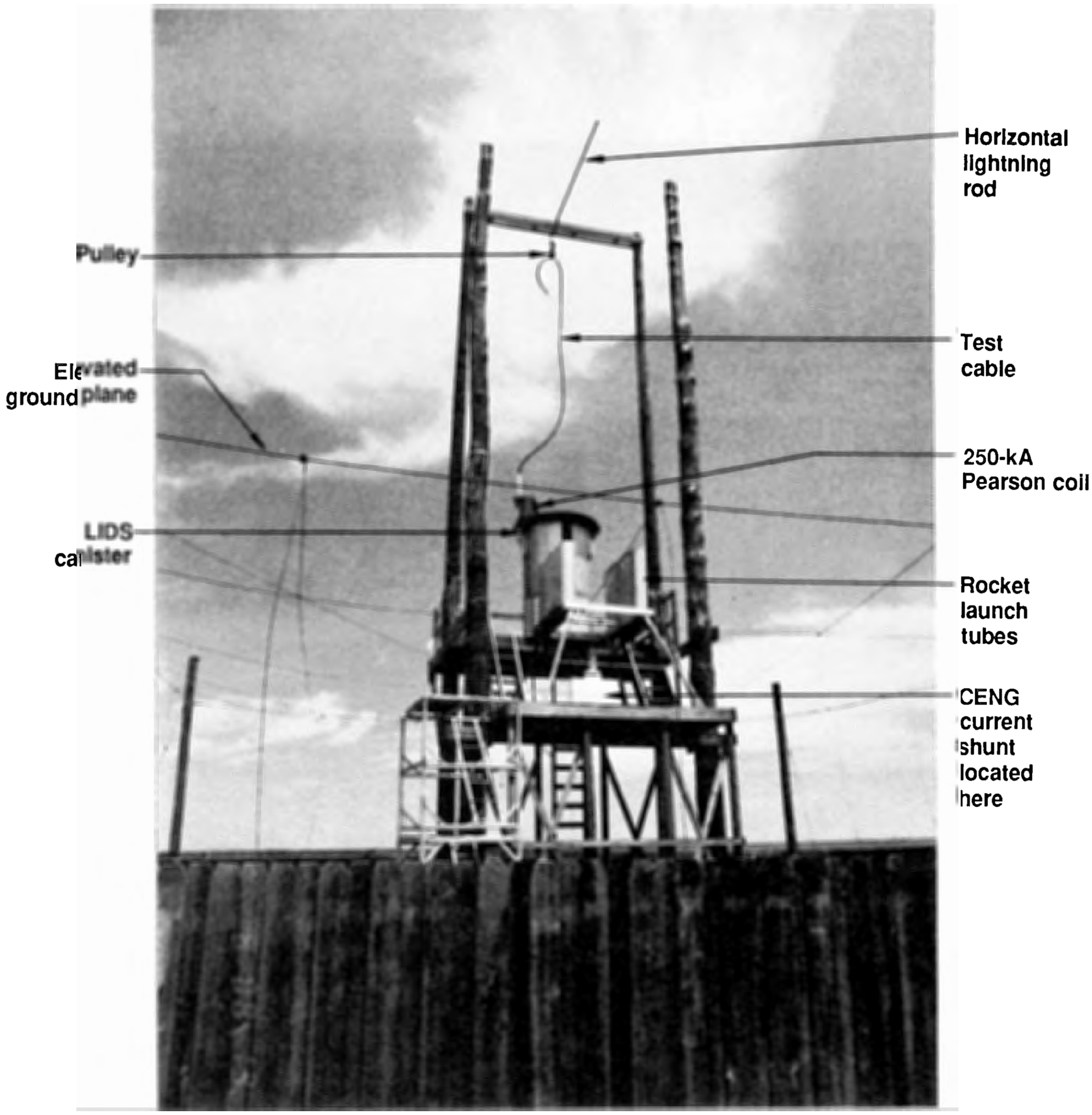

Figure 10. RTLP launch platform and LIDS canister. A horizontal pipe served as a lightning rod to conduct lightning transients to the LIDS.

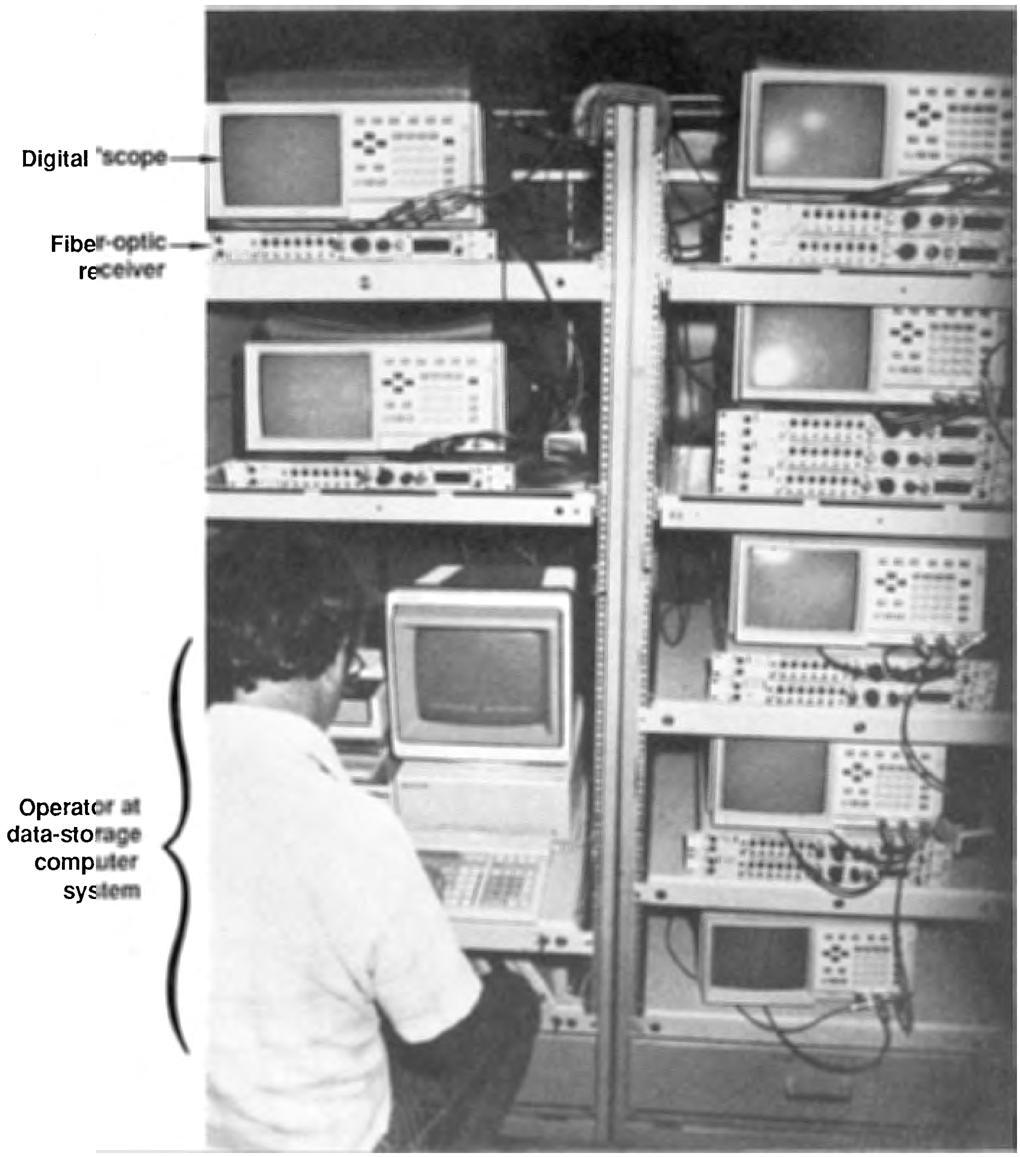

Figure 11. The RTLP data-acquisition and storage system.

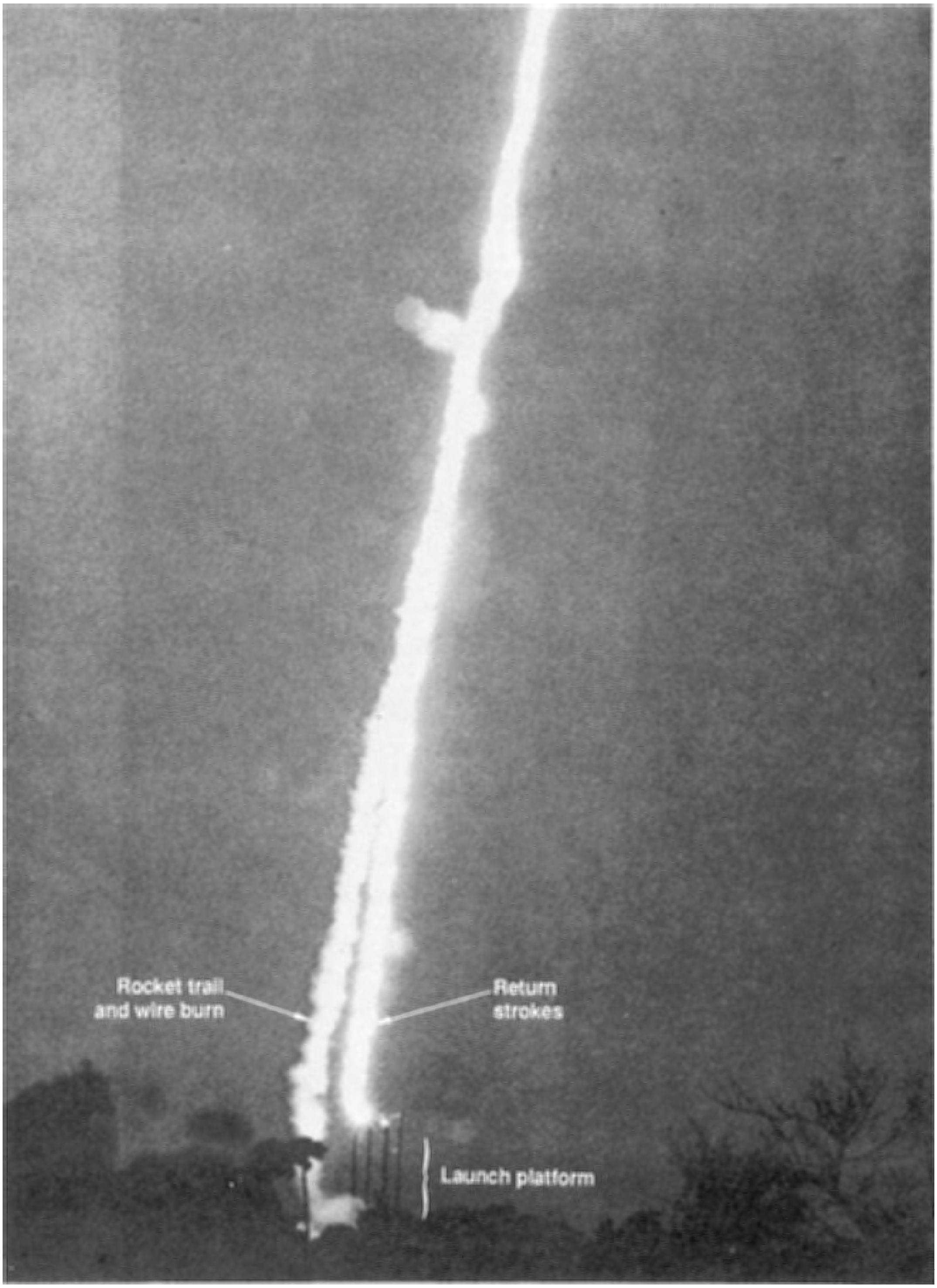

Figure 12. A vaporized wire trail and the resulting triggered lightning return stroke attached to the horizontal rod. (Photo by M. Denemark, *Florida Today*.)

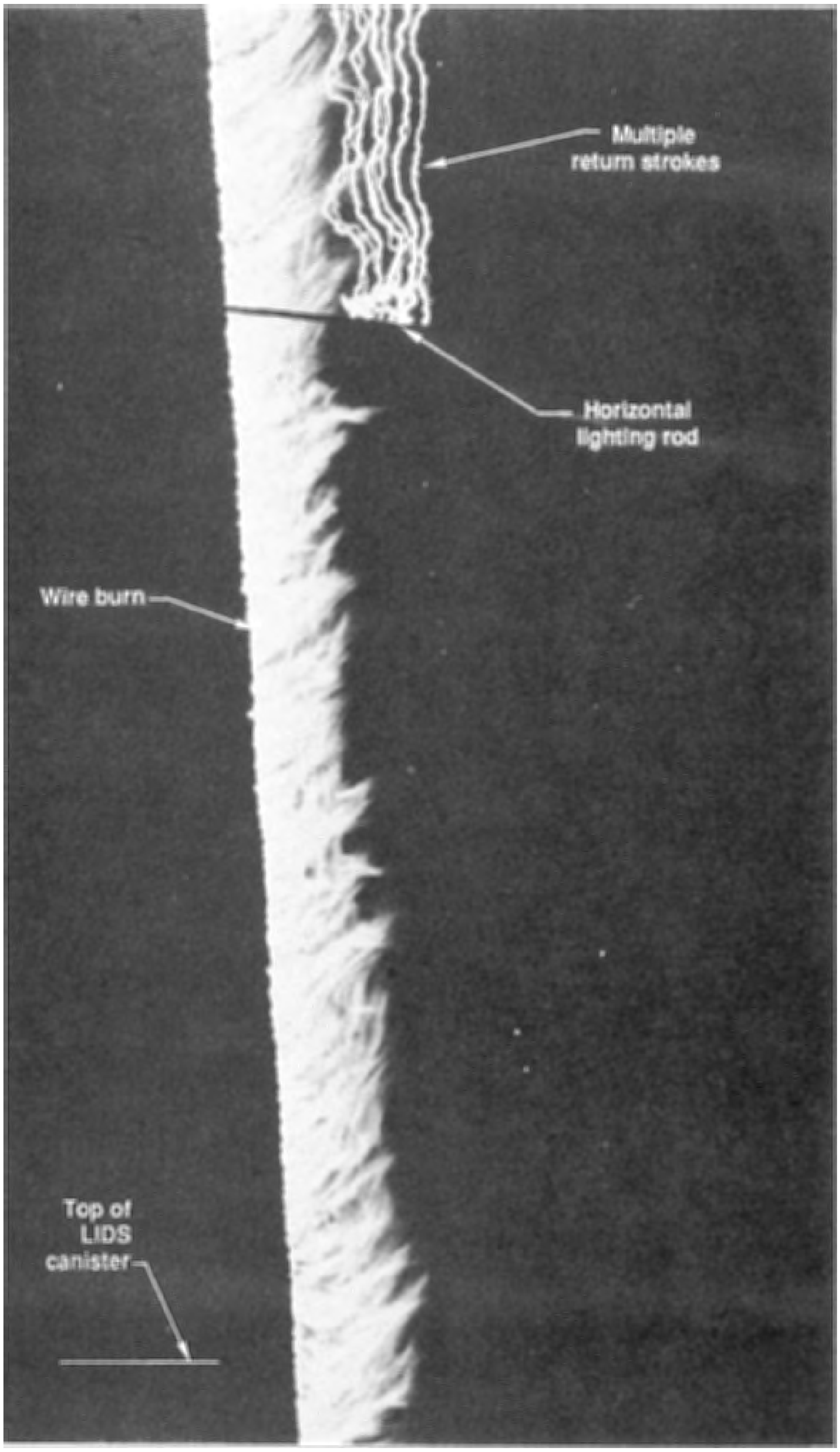

Figure 13. A close-up of a wire burn and multiple return strokes attached to the horizontal lightning rod.